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			5c. PROGRAM ELEMENT NUMBER 611102		
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14. ABSTRACT The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexoelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in					
15. SUBJECT TERMS flexoelectricity, biomembranes, defects, fluctuations					
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## Report Title

Final Report: Flexoelectricity in PZT Nanoribbons and Biomembranes

### ABSTRACT

The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexoelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in several one and two-dimensional electromechanical problems. A key highlight of this paper was a flexoelectric reciprocal theorem. We used the formulation in this paper to solve for the electrical and mechanical fields around point defects, dislocations and cracks in flexoelectric solids. We confirmed the important role of flexoelectricity in the immediate vicinity of defects due to the existence of large strain gradients. A key highlight of this paper was that we showed that flexoelectricity is the most likely mechanism behind electromagnetic radiation from moving dislocations and cracks in ice. We also collaborated with Michael McAlpine in Princeton on several projects. We studied the electromechanical response of neuronal cells, energy harvesting using pyro-para-electricity and a new way of producing PZT nanoribbons for energy harvesters.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

Received

Paper

08/20/2014	1.00	Tal Kramer, Thanh D. Nguyen, Nikhil Deshmukh, Prashant K. Purohit, Michael J. Berry, Michael C. McAlpine, John M. Nagarah. Piezoelectric nanoribbons for monitoring cellular deformations, Nature Nanotechnology, (09 2012): 587. doi: 10.1038/nnano.2012.112
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**TOTAL: 1**

Number of Papers published in peer-reviewed journals:

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(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
01/09/2015 7.00	Huai-an Chin, Sheng Mao, Chiao-Ti Huang, Kwaku K. Ohemeng, Sigurd Wagner, Prashant Purohit, Michael McAlpine. Pyro-paraelectricity, Extreme Mechanics Letters, (01 2015): 0. doi:
01/09/2015 8.00	Thanh Nguyen, Sheng Mao, Yao-Wen Yeh, Prashant Purohit, Michael McAlpine. Nanoscale flexoelectricity, ADVANCED MATERIALS, (02 2013): 946. doi:
<b>TOTAL:</b>	<b>2</b>

Number of Papers published in non peer-reviewed journals:

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(c) Presentations

Number of Presentations: 10.00

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
<b>TOTAL:</b>	

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received

Paper

08/20/2014 4.00 Prashant\_Purohit. Tension dependent growth and retraction of neurites, IUTAM symposium on soft active materials. 15-MAY-14, . : ,

**TOTAL: 1**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**(d) Manuscripts**

Received

Paper

01/09/2015 6.00 Prashant Purohit, Sheng Mao. Defects in flexoelectric solids, Journal of the Mechanics and Physics of Solids (11 2014)

08/20/2014 2.00 Sheng\_Mao, Prashant\_Purohit. Insights into flexoelectric solids from strain gradient elasticity, Journal of Applied Mechanics (03 2014)

08/20/2014 3.00 Kellye\_Cung, Booyeon\_Han, Thanh\_Nguyen, Sheng\_Mao, Yao-Wen\_Yeh, Shiyu\_Xu, Rajesh\_Naik, Gerald\_Poirier, Nan\_Yao, Prashant\_Purohit, Michael\_McAlpine. Biotemplated synthesis of PZT nanowires, Nano Letters (11 2013)

08/20/2014 5.00 Thanh\_Nguyen, Ian\_Hogue, Kellye\_Cung, Prashant\_Purohit, Michael\_McAlpine. Tension induced neurite growth in microfluidic channels, Lab on a Chip (07 2013)

**TOTAL: 4**

Number of Manuscripts:

Books

Received      Book

TOTAL:

Received      Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Sheng Mao	1.00	
<b>FTE Equivalent:</b>	<b>1.00</b>	
<b>Total Number:</b>	<b>1</b>	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Prashant K Purohit	0.10	
<b>FTE Equivalent:</b>	<b>0.10</b>	
<b>Total Number:</b>	<b>1</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

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### Names of Personnel receiving masters degrees

<u>NAME</u>
<b>Total Number:</b>

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### Names of personnel receiving PHDs

<u>NAME</u>
<b>Total Number:</b>

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### Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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Sub Contractors (DD882)

## **Inventions (DD882)**

### **Scientific Progress**

The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexoelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in several one and two-dimensional electromechanical problems. A key highlight of this paper was a flexoelectric reciprocal theorem. We used the formulation in this paper to solve for the electrical and mechanical fields around point defects, dislocations and cracks in flexoelectric solids. We confirmed the important role of flexoelectricity in the immediate vicinity of defects due to the existence of large strain gradients. As a highlight of this paper we showed that flexoelectricity is the most likely mechanism behind electromagnetic radiation from moving dislocations and cracks in ice.

Funds from this grant also supported our collaboration with Michael McAlpine at Princeton University. We collaborated on several projects. In the first project we studied the electromechanical response of neurons. We showed that changing the potential difference across the neuronal membrane causes mechanical deformations that can be detected by PZT nanoribbons. In a second project we studied the force dependent growth of neurons in micro-fluidic channels. We wrote a model based on the polymerization of microtubules that could accurately capture the force dependent growth of the neuron. In a third project we showed how bio-templated PZT nanowires could be used to produce currents when subjected to cyclic deformations. Our contribution to this paper was an electromechanical model describing the current generation. In a fourth collaboration we showed that when a BST thin film is subjected to cyclic temperature changes then it can produce current due to flexo-electricity. Our contribution to this paper was to write a model for the coupling of the large strain gradient in the thin films to the charge separation across it, and an analysis of the convective, conductive and radiative heat transfer that causes the transient heating and cooling of the film resulting in the flow of electrical charges. We also wrote a review paper in Advanced Materials summarizing nanoscale flexoelectricity.

### **Technology Transfer**